Class 11 – Introduction to Surface BRDF and Atmospheric Scattering

Class 12/13 - Measurements of Surface BRDF and Atmospheric Scattering
Directional Reflectance of Surfaces and Particles

• Surface color
• Reflectance by a smooth and flat surface
• Reflectance of a rough surface
• Reflectance by particles over a surface
• Reflectance by particles or molecules in suspension in the atmosphere
Solar (reflective) spectral domain
Vegetation reflection

Spectral dependence
(for angular dependence, see Lecture 2)

Frequent measure: Normalized Difference Vegetation Index

\[ NDVI = \frac{R_{NIR} - R_{VIS}}{R_{NIR} + R_{VIS}} \]

Figure thanks to Tamas Varnai/JCET - UMBC
Different Types of Reflectors

- Specular reflector (mirror)
- Nearly Specular reflector (water)
- Diffuse reflector (lambertian)
- Nearly diffuse reflector
- Hot spot reflection

Figure thanks to Eric Vermote - UMD
Fresnel Curves for Flat and Smooth Surfaces

http://en.wikipedia.org/wiki/Fresnel_equations
Solar Energy Paths

Figure thanks to Eric Vermote - UMD
Observation Geometry

- Solar zenith angle
- View zenith angle
- Relative azimuth angle

Figure thanks to Eric Vermote - UMD
Different Types of Reflectors

Specular reflector (mirror)

Nearly Specular reflector (water)

diffuse reflector (lambertian)

nearly diffuse reflector

Hot spot reflection

Figure thanks to Eric Vermote - UMD
Perfect Lambertian Reflector

Radiance of the Perfect Lambertian Reflector

\[ \int_0^{\pi} \int_0^{2\pi} \mathcal{RPLF}(\theta_S, \theta, \phi) \cos(\theta) \sin(\theta) d\theta d\phi = E_s \cos(\theta_s) \]

\[ \mathcal{RPLF}(\theta_S, \theta, \phi) = \mathcal{E}_s \cos(\theta_S) \]

Isotropic radiation

\[ \rho_{\text{Perfect Lambertian reflector}}(\theta_S, \theta_V, \phi) = 1 \]

\[ \rho_{\text{Lambertian reflector}}(\theta_S, \theta_V, \phi) = \rho \]

Figure thanks to Eric Vermote - UMD
Surface characterization

In atmospheric studies, surface often characterized using bulk properties:

**Albedo:**

\[ \rho = \frac{F_\uparrow}{F_\downarrow} \]

**BRF** (Bidirectional Reflection Function) or Simply **Reflectance** \((R)\):

\[ BRF = \frac{\pi \cdot I}{\mu_0 \cdot F_0} \]

**BRDF** (Bidirectional Reflection Distribution Function):

\[ BRDF = \frac{BRF}{\rho} \]

Remote sensing

**CAR (Cloud absorption radiometer) measurement strategy**

Figure thanks to Tamas Varnai/JCET - UMBC
Surface reflection patterns

EXPLANATION OF FEATURES

- **Cloud droplet phase function (0.63 µm, red light)**

- **CAR measurements**
  - **Water Clouds: 0.682 µm**
  - **Savanna Vegetation: 0.870 µm**
  - **Salt Pan: 0.682 µm**
  - **Ocean: 0.472 µm**

- **Reflection Function**

Figure thanks to Tamas Varnai/JCET - UMBC
Sun glint as seen by MODIS

Gray level temperature image

Figure thanks to Tamas Varnai/JCET - UMBC
Sea surface

Spectral dependence:
dark in infrared (?)
Cox and Munk model (1954):
• assumes sine waves
• parameterizes reflectance as a function of wind speed (2-10 m/s)

Probability of surface orientation ($U$ is wind speed):

$$
\rho(\tan \theta_n) = \frac{1}{\pi \sigma^2} \exp\left( -\frac{\tan^2 \theta_n}{\sigma^2} \right)
$$
\[ \sigma^2 = 0.003 + 0.00512U \]

Current research:
• wider wind range (e.g., white caps, multiple reflection),
  • underwater scattering (plankton)

Figure thanks to Tamas Varnai/JCET - UMBC
Snow reflection

Nearly uniform spherical crystals

Size increases and extinction coefficient decreases with age
- Fresh snow: ~50 µm
- Old dry snow: ~200 µm
- Wet snow: ~1000 µm (=1 mm)

<table>
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<th>Radius (µm)</th>
<th>Density (g/cm³)</th>
<th>N (1/m³)</th>
<th>VEC (1/m)</th>
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<td>1000</td>
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</tbody>
</table>

\[ \sigma \approx \frac{3 \ LWC}{2 \ \langle r \rangle \rho} \]

Figure thanks to Tamas Varnai/JCET - UMBC
Snow reflection

Angular dependence

Explain dependence on solar elevation and wavelength

Figure thanks to Tamas Varnai/JCET - UMBC
Scattering by Particles:

- The scattering angle, $\Theta$, is the relative angle between the incident and the scattered radiation.
Rayleigh/molecular scattering

1/4

- Rayleigh or molecular scattering refers to scattering by atmospheric gases, in that case:

\[ P(\Theta) = \frac{3}{4} \left( 1 + \cos^2(\Theta) \right) \]
Rayleigh phase function

Idea of polarization, sources of polarization

Two components of variations in electric field
Dipole scattering depends on angle between $E$-variations and plane of scattering (specified by incoming and outgoing directions):

- **Perpendicular component:** $P(\Theta) = 1$
- **Parallel component:** $P(\Theta) \propto \cos^2(\Theta)$

**Overall:**

$$P(\Theta) = \frac{3}{4}(1 + \cos^2 \Theta)$$

Clear-sky polarization

Multiple scattering reduces polarization (e.g., clouds)

Figure thanks to Tamas Varnai/JCET - UMBC
Phase diagram for Rayleigh scattering

Parallel Component + Perpendicular Component = Net

$\cos^2 \Theta + 1 = \cos^2 \Theta + 1$
Phase diagrams for aerosols
Phase function plots

Figure 3.13 Normalized phase functions for cloud droplets (∼10 μm), aerosols (∼1 μm), and molecules (∼10⁻⁴ μm) illuminated by a visible wavelength of 0.5 μm, computed from the Lorenz–Mie theory.

Figure thanks to Tamas Varnai/JCET - UMBC
Non-spherical particles

**T-matrix method**: Rotational symmetrical particles: 
Series expansion uses spherical Henkel and Bessel functions, etc. 
Free public codes (FORTRAN) available, fast

**FDTD method**: irregular particles
(e.g., ice crystals, aerosol)

Finite difference time domain
Computationally expensive
Codes available (commercial too)

Figure thanks to Tamas Varnai/JCET - UMBC
Sample ice crystal phase functions

22° and 46° halos

Figure thanks to Tamas Varnai/JCET - UMBC
Snow at longer wavelengths

Thermal infrared: Snow emissivity really high (~0.99)

Microwave:
One issue is closeness of particles
Rayleigh approximation so-so: 10-100 GHz or perhaps 0.5 to 5 cm wavelength
(snow grain size: 50µm when fresh, 1000µm when old and wet)

Remote sensing: compare effectiveness of scattering, emission at 2 frequencies
(e.g., 19, 37 GHz)

Snow Emissivity Spectra

Figure thanks to Tamas Varnai/JCET - UMBC
Sea ice

Fresh ice, like a mirror

Often covered by snow

Melting ponds (albedo decreases in summer)

Figure thanks to Tamas Varnai/JCET - UMBC
Sea ice: leads and pressure ridges

Figure thanks to Tamas Varnai/JCET - UMBC
Sea ice: inside

Ice itself: absorption (hence blue color), but not much scattering except algae at boundaries

Scatterers

![Figure 1. Vertical thick section of first-year sea ice taken from interior first-year ice at a depth of approximately 80 cm. Sample thickness is approximately 5 mm.](Image)

Figure thanks to Tamas Varnai/JCET - UMBC
Sea ice: inside

Close-up photo of sea ice

Bubbles in near-melting ice

Vertical structure of sea ice

Figure 4. Photomosaic of vertical thin section of first-year ice in transmitted light at -15°C. Ten boxed subregions were used for counting inclusions. Overall dimensions of scene are 12.1 × 4.7 mm, with 2 mm thickness. Arrows indicate examples of (1) brine tubes, (2) brine pockets, (3) bubbles, (4) drained inclusions, (5) transparent areas, and (6) poorly defined inclusions. (right) An enlargement of box outlined with dashed line. Arrows indicate (A) solitary brine pocket, (B) cluster of small pockets, and (C) string of pockets.

Figure thanks to Tamas Varnai/JCET - UMBC
Extra Slides:
Scattering by large particles—geometric optics

If $x > 1000$, diffraction is not too important (what examples?)

**Snell’s laws** (1625): \[ \theta_{\text{out}} = \theta_{\text{in}}, \quad \frac{\sin \theta_1}{\sin \theta_2} = \frac{c_i}{c_2} = \frac{m_{r,2}}{m_{r,1}} \]

Critical angle: $\theta = 90^\circ$ (sin($\theta$)=1),
If $\theta$ is greater than critical angle: internal bouncing

For light coming out of water, critical angle is about 50°.

**Nice online demonstration** (http://www.physics.northwestern.edu/ugrad/vpl/optics/snell.html)
Sample Mie phase functions

Cloud droplet, \( r = 10 \, \mu m, \lambda = 0.55 \, \mu m \) (green)

Why no ripples?
Why no polarization?

Figure from a book

Figure thanks to Tamas Varnai/JCET - UMBC
Corona, aureole

Figure thanks to Tamas Varnai/JCET - UMBC
Aerosol size effect on Scattering:

Fine particles from smoke

Coarse dust particles

Fine particles from smoke